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AGGRESSIVE MANEUVERS

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MARCH 2005

Final Report for 17 October 2000 – 07 December 2004

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STINFO FINAL REPORT

AIR VEHICLES DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542

NOTICE

PAO Case Number: AFRL/WS-06-1046, 20 April 2006

THIS TECHNICAL REPORT IS APPROVED FOR PUBLICATION.

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14. ABSTRACT

Operation of future autonomous vehicles in high-stress mission environments, such as air combat, suppression of enemy air defenses, and urban warfare, requires high maneuverability and adaptation to uncertain dynamics and environmental conditions. Traditional control algorithms impose performance limitations that fall far short of what can be achieved by skilled human pilots. The main objective of this project was to develop and demonstrate the ability for aggressive on-line maneuver trajectory generation. The goal was to demonstrate autonomous vehicle maneuvering capability well beyond the level typical in today's autonomous air vehicles. A second objective was to integrate the aggressive flight control technology into the SEC demonstration platform.

The task was structured in two experiment demonstration phases where the first phase involved demonstrating our aggressive autonomous guidance capability on Draper's aggressive flight test vehicle. The second phase integrated and demonstrated these algorithms on the SEC rotary wing demonstrator platform – Georgia Institute of Technology's Yamaha RMAX helicopter.

15. SUBJECT TERMS
Unmanned Vehicles, Aggressive Maneuvering, Software Enabled Control, Autonomous Maneuvering, Trajectory Generation

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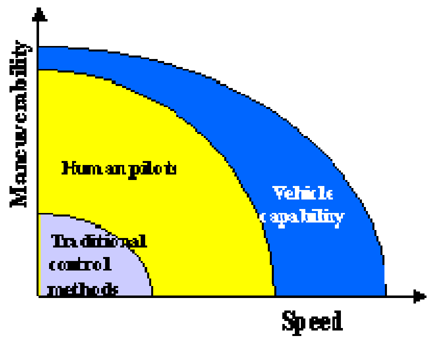
Task Overview

Operation of future autonomous vehicles in high-stress mission environments, such as air combat, suppression of enemy air defenses, and urban warfare, requires high maneuverability and adaptation to uncertain dynamics and environmental conditions. Traditional control algorithms impose performance limitations that fall far short of what can be achieved by skilled human pilots. The main objective of this project was to develop and demonstrate the ability for aggressive on-line maneuver trajectory generation. The goal was to demonstrate autonomous vehicle maneuvering capability well beyond the level typical in today's autonomous air vehicles. A second objective was to integrate the aggressive flight control technology into the SEC demonstration platform.



The task was structured in two experiment demonstration phases where the first phase involved demonstrating our aggressive autonomous guidance capability on Draper's aggressive flight test vehicle. The second phase integrated and demonstrated these algorithms on the SEC rotary wing demonstrator platform – Georgia Institute of Technology's Yamaha RMAX helicopter.

Phase 1: 7/00-11/02

The first phase of the project focused on integrating and flight testing this aggressive maneuver generation logic on Draper's aggressive flight test vehicle. This vehicle is a small, radio-controlled (RC) helicopter, an XCell-60 that is capable of aerobatic maneuvers. Draper has developed a small GPS/INS-based avionics system that turns this RC vehicle into an autonomous vehicle.

Phase 2: 4/02-7/04

In this phase of the project, Draper collaborated with Georgia Tech to transition our hybrid maneuver guidance logic onto the SEC program demonstrator platform and demonstrated the usefulness of our agile maneuvering algorithm in a militarily significant mission. Draper first acquired Georgia Tech's flight simulation software of the GT-RMAX – Georgia Tech's RMAX helicopter – and integrated the agile maneuvering guidance system into this simulation. This same flight code was then transitioned to Georgia Tech for subsequent HWIL testing and flight-tests towards mid and final term exams. We defined and demonstrated an autonomous sniper avoidance scenario during an urban reconnaissance mission in which the rapid agile maneuvering improves survivability so that we can showcase the new guidance & control technology in the OCP platform.

Agile Maneuvering Guidance Algorithm Overview:

In our approach, several "maneuver primitives" – elemental moves that aggressively segue between different trim flights via elemental aerobatic moves – are recorded for the particular vehicle. These primitives are analyzed in terms of the total displacement they achieve in state-space, and how much they cost to execute. This data is tabulated and stored for onboard access for the onboard trajectory planner when it needs to plan or re-plan a trajectory. Offline, a motion-planning algorithm computes the "cost-to-go" from one grid coordinate in space to the origin by "optimally" stitching together maneuver primitives and trim flight conditions. Our design calculates cost-to-go as the minimum time required to achieve the end point from any location to the origin. On-line, the onboard part of the planner synthesizes a trajectory command by evaluating *feasible* trim and aggressive maneuver options, computes where each move would take the aircraft relative to the way-point and then accesses the stored cost-to-go table to determine the minimum cost between the new point and the goal points. We use the origin-based cost-to-go table by performing a change of reference frame from inertial coordinates to one where the origin is centered at the way-point of interest. The planner selects the trim or maneuver option such that its cost (time duration) + cost-to-go costs the least of all feasible options. A feasible trim or maneuver option is identified as follows. The rule of this hybrid controller system is that the helicopter in trim flight must either remain in that particular trim or else transition into a maneuver that commences from that trim. Hence a feasible transition is to either continue in that particular trim configuration or else attempt a maneuver defined from that trim. In our hybrid system approach, we do not allow a maneuver to be aborted; it must be completed as interrupting an aggressive, agile maneuver may compromise the stability of the closed loop system.

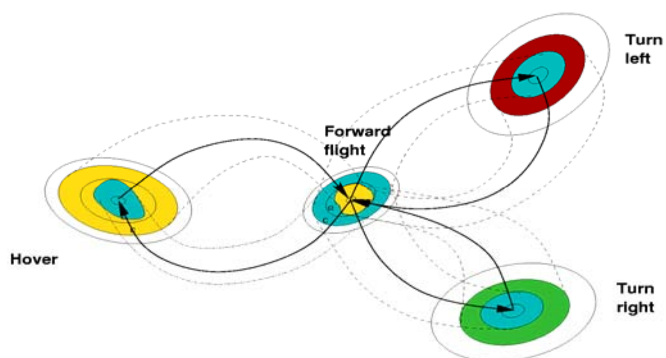


Figure 2: *Hybrid transition control architecture showing the trims at the nodes or stationary points of the transition diagram and the arrows between the nodes indicating maneuvers. A system can remain in trim indefinitely. A transition or maneuver, however, is completely parameterized by its initial (trim) condition, terminal (trim) condition, and the duration of that maneuver.*

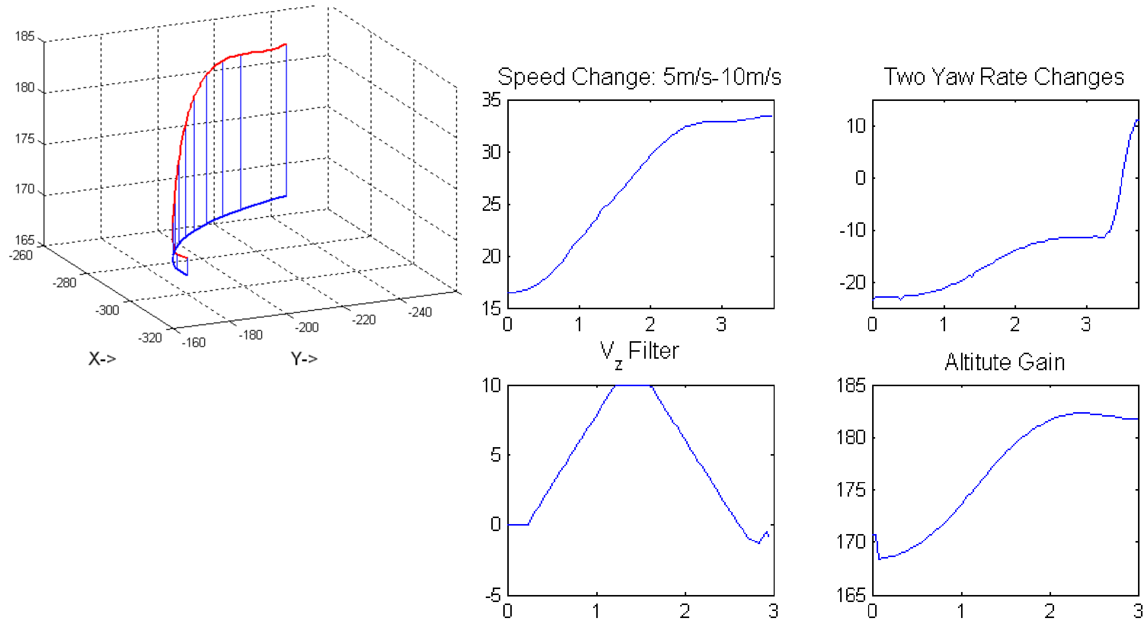


***Figure 3**: Shows an example of two maneuvers and an intervening trim that achieve a 60degree heading change, speed change from 15fps to 33fps, and altitude gain maneuver that includes vertical acceleration to a constant ascent speed, and vertical deceleration to hold altitude. This sequence of maneuver – trim – maneuver - trim produces the trajectory shown in the figure at left in red.*

This approach synthesizes dynamically realizable trajectories. The dynamics of the vehicle explicitly define the maneuver and trim bases, and correspondingly limit the reachable set of maneuvers by the vehicle's dynamic constraints. The algorithm uses dynamic programming to synthetically append maneuver elements to form optimal trajectories that minimize the mission costs; dynamic programming also enables the method to synthesize trajectories in real-time. The approach is different from traditional planning approaches that plan geometric trajectories independent of the vehicle's dynamics. These approaches only consider vehicle dynamics when the controller has to execute the geometrically planned trajectory and therefore do not take advantage of the true maneuvering capabilities of the vehicle. Our approach corrects this limitation because it explicitly designs the trajectory from maneuver elements that are rooted in the vehicle's dynamics.

Because vehicle models are never perfect, or the environment may sustain unexpected, unmodeled disturbances and obstacles that were not known *a priori* when the trajectory planner first synthesized its nominal trajectory, the nominal trajectory may not be perfectly realizable practically. This is possible even with a feedback controller to execute the plan. As a result, we drive our motion planner in an outer feedback loop, so that it repeatedly synthesizes trajectories to the goal state as a function of the vehicle's present location - which may be different from where the motion planner predicted it would be at this time - and the most recent snapshot of the environmental model. This feedback process ensures that the guidance loop is robust to unmodeled environment features, disturbances, and uncertainties in the vehicle model.

Militarily-Relevant Demonstration Scenario and Technology Development

The rotor-wing demonstrations were staged at the McKenna MOUT site. We demonstrated our real-time dynamics-based agile maneuvering guidance capability in an urban surveillance

mission with real-time threat avoidance from a sniper located in a building within the town. In this scenario, the GTMAX starts from hover behind a thicket of trees over the airstrip, flies along the airstrip in front on the town, turns towards the town and emerges from behind another pair of trees. Its mission plan is specified *a priori* by way of a sequence of waypoints that are supplied to the GTMax mission planner via its ground control station (GCS) at initialization. The mission planner feeds waypoints one at a time to the onboard guidance logic as the helicopter hits each waypoint and the guidance block declares itself done with that waypoint. Nominally, the guidance logic will attempt to fly the mission plan as aggressively as possible which in our case implies that it will attempt to complete the mission in minimum time and at the highest allowable mission-specified speed (35feet per second in this case) and still approach within approximately 12 feet (3.5 meters) of each waypoint.

Figure 4: *Figure at left shows an image of McKenna MOUT with mission plan – 10 waypoints superimposed on the map. The figure at the left shows a matlab regeneration of the same map with a nominal trajectory obtained after an example flight.*

During the flight, we allow a user – the pilot on ground control– to designate a sniper firing from some coordinates in a particular nominal direction. When the GCS designates a particular sniper location and firing heading, we simulate a gun shot detector such as one that McKenna MOUT has been testing in the 2003-2004 period. This gun-shot detector sends an alarm with sniper coordinates and expected firing direction when the helicopter enters his firing cone. The threat-aware planner uses that threat information and a map of the urban area to identify nearby buildings and their heights relative to the sniper such that it can drop below the sniper's view of the roof deck and thus mask itself from the now known sniper for protection. The guidance logic rapidly updates the trajectory and synthesizes a new dynamics-based agile trajectory that will achieve the masked coordinates that the threat aware planner proposed. The threat planner continuously monitors and re-derives the safe flight altitude to command to the guidance logic so that the helicopter is always masked. The

helicopter flies at this masked altitude until it has turned the corner or it has exceeded the sniper's firing range at which point it regains its commanded altitude.

In practice, to prevent the GCS pilot from having to make up sensible numbers for geographical location, sniper heading and his viewing/firing cone, we pre-specified 5 different candidate sniper locations inside the McKenna MOUT site buildings with their viewing and firing cones. This allows the pilot to have to only enter 1, 2, 3, 4, or 5 when he wishes to designate a sniper. The gun-shot simulator then reads off the associated sniper coordinates, calculates the helicopter's location relative to the sniper's viewing window and produces the safe flight altitude from the urban terrain map based on this calculation. All information interior to the threat calculation and the guidance logic is independent of whether the sniper locations are fixed or flexible.

We also integrated autonomous obstacle avoidance into the guidance logic although we did not test fly this. This development only went as far as software in the loop simulation tests. We implemented a multi-threaded, multi-rate architecture in which an obstacle avoiding component synthesizes trajectories in a receding horizon way by planning upto 30meters into the future. It resynthesizes the trajectory once every second. In the meanwhile, the primary guidance logic "feeds" the first 1 second worth of the planned trajectory to the control modules at its nominal 50Hz rate. The reason for this multi-rate architecture is that we found that it is impossible to plan constraint-free trajectories at the nominal 50Hz operating rate. Georgia Tech did not wish to fly a multi-threaded architecture, hence we did not HWIL or test fly it.

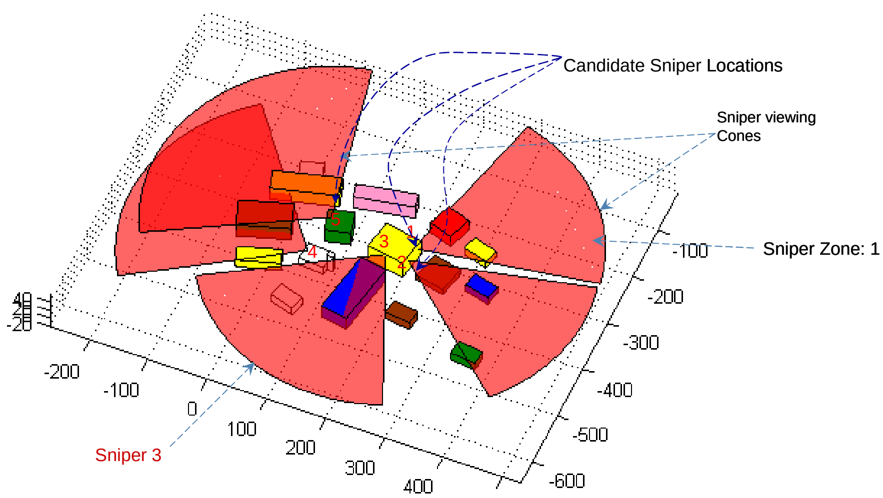


Figure 5: *Figure showing 5 candidate sniper locations and respective viewing cones superimposed on urban terrain map showing building locations.*

Status and Results from Flight Tests

Phase 1:

To flight test autonomous guidance, navigation, and control algorithms, Draper had developed a small, autonomous, aerobatic helicopter under internal funding. Draper modified our helicopter GN&C software to support flights using the agile, hybrid-logic. In addition, Draper had begun flight testing with the avionics system integrated with the flight vehicle.

In November 2002, completed testing was discontinued due to the hardware failures and direction to focus on Phase 2.

Phase 2 Summary and Flight Test Analysis:

A flight test profile is summarized here. We commenced flight tests in October 2003 when we tested our dynamic-model and splines based maneuver elements. We took a conservative approach to these maneuver-based flight tests by flying multiple (approximately 60 out of a possible 125) maneuvers. In our first 4 flights we evaluated these 60 maneuvers synthetically produced from analytical spline functions by first under-approximating the control limits by about 20%. We first tested these more conservative maneuvers. When these were successful, we tested the maneuvers produced by using the actual control limit definitions provided to us by Georgia Tech. These tests showed us that we were not saturating any controls significantly or for long by flying the actual control limits and thereafter we have always flown with these more aggressive maneuvers obtained from the 100% limits.

In February, 2004 we flew two different racetracks defined as a sequence of waypoints. The objective here was to test the optimal, hybrid-control based trajectory synthesis algorithm. The first racetrack was a wide racetrack; the second racetrack is a much tighter track which we found from simulations that a conventional guidance algorithm provided in the GT flight simulation package cannot complete. Using Draper's hybrid control approach, the helicopter successfully completes this quite aggressive trajectory.

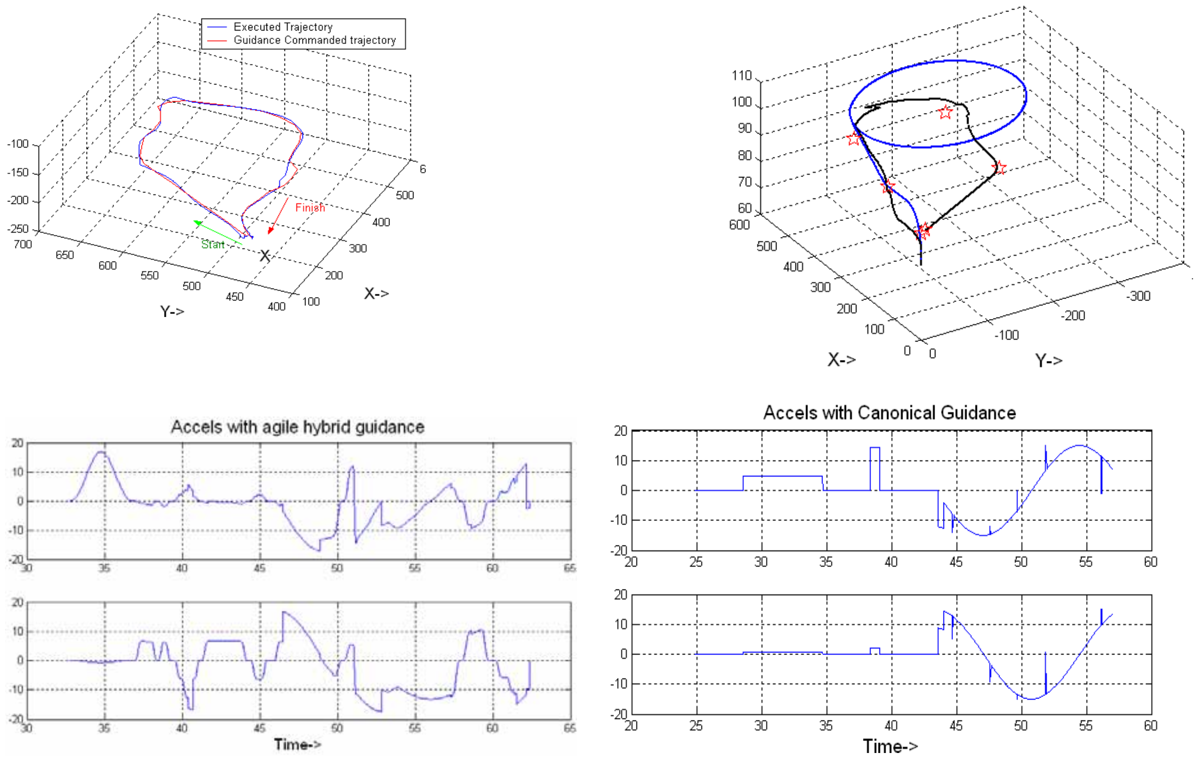
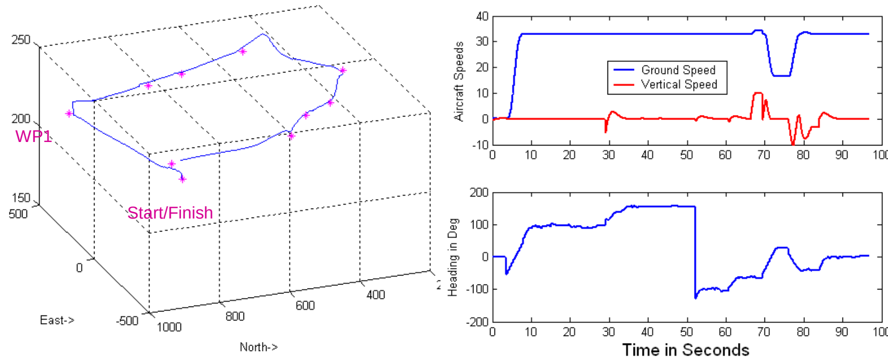


Figure 6: *Plots showing the helicopter flying the tight racetrack. The figure on the top left shows commanded and achieved flight data. The figure on the top right compares simulation-obtained plots of the Draper Guidance logic based trajectory (in black) and a conventional, geometry-based guidance algorithm that is unable to accommodate the tight turn at the top of the racetrack. The lower row of figures show X and Y acceleration profiles – a subset of the feedforward control history – produced by the Draper Guidance logic (flight data) vs. the conventional guidance strategy to achieve the trajectories. The reader will observe that the profiles are qualitatively similar in the early parts of the trajectory; the dynamics-based trajectory profile does not induce step changes in accelerations but rather, it commands smooth functions. However, the profiles are otherwise similar to accommodate the acceleration from hover to the 35fps commanded speed, steady speeds between the first, second and third waypoints, and then the start of the heading change motion. However, at about 50 seconds, the dynamics-based guidance logic induces an opposite thrust from the direction of the smooth sinusoid at that point in time. This 1.5 second long command is noticeably absent in the canonical guidance command profile. This momentary pulse in the tail-rotor torque produces a significant side-slip that slews the helicopter nose around, and then it resumes its normal heading change maneuver. This allows the dynamics-based guidance logic to complete the racetrack that the conventional guidance did not.*

Subsequently, we made software modifications to the offline calculations that included better ways to compute the non-convex cost-to-go function; these modifications also resulted in generally faster but smoother flights between waypoints. Repeated flight tests supported this. At this point, we also flew the McKenna mission plan.



Flight Test Data: McKenna Circuit Trajectory

Figure 7*: Flight data of nominal route around McKenna. The plots on the right show speeds – ground relative vehicle speed and vertical flight speed are plotted in the top plot, the aircraft heading angle is shown in the lower plot.*

Finally, we implemented and tested the threat avoidance, masking calculations into the software to implement the sniper avoidance. The following figures show a sniper's views (sniper number 3 from the threat map above) before and after including the sniper avoidance automatic planning algorithm.

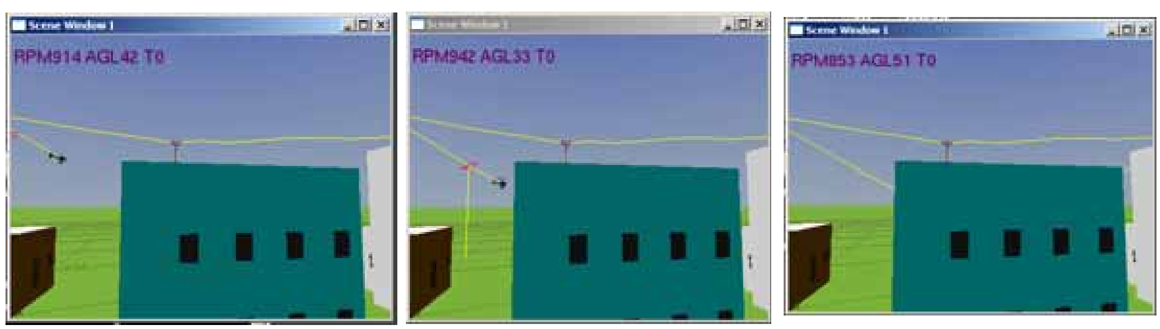


Figure 8: *Figures show view from sniper 3's view. Yellow traces mark the helicopter's trajectory. The continuous yellow trace present in all three plots shows the helicopter trajectory without automatic avoidance. The figures also show the helicopter ducking down behind the intervening building to mask itself once the sniper started firing on the helicopter and thus "revealed" his coordinates to the gun-shot detector, when the helicopter entered his field of view. The helicopter completes the remainder of the trajectory masked behind the building. The helicopter increases its chances of survival because it has significantly reduced its exposure time to the sniper.*

In all, Draper Laboratory flew approximately 24 flights over about 10 flight test days.

Phase 2 Replans:

Our original plans had involved autonomous obstacle avoidance to avoid buildings, trees, wires etc. However, in light of our finding that it was exceedingly difficult to implement obstacle avoidance in a guidance module that must operate at a 50Hz rate (we found that

about a 1 or 2Hz (or slower) rate is necessary to handle the computational burden of producing paths in cluttered spaces), and GT's hesitation to fly our multi-rate, multi-threaded controller architecture, we abandoned our plans to demonstrate obstacle avoidance in flight. Instead we focused on our other and more important goal: to demonstrate autonomous onboard threat avoidance. This we were successfully able to implement and demonstrate with the single threaded architecture operating at 50Hz.

Draper Laboratory Contributors to Software Enabled Control Program

Felsa Satlow, Program Manager, 1999-May, 2004

Judy Miller, Program Manager, June 2004-Nov. 2004

Dr. Leena Singh, Principal Investigator 2002-Nov. 2004

Dr. Brent Appleby, Principal Investigator, 1999-2002

Dr. Marc McConley, Contributor, 1999-2001

Mr. John Plump, Contributor, 2001- 2002

Publications List

"Hybrid Control for Aggressive Maneuvering of Autonomous Aerial Vehicles", M. McConley, M. Piedmonte, B.D. Appleby, E. Frazzoli, E. Feron, M.A. Dahleh. In, 19th Digital Avionics Systems Conference, October 2000.

"Software-Enabled Control: Autonomous Agile Guidance and Control for a UAV in Partially Unknown Urban Terrain", L. Singh, J. Plump, M. McConley, B. Appleby. In AIAA-Guidance Navigation and Control Conference 2003.

"Autonomous Guidance for Agile UAV Maneuvering", L. Singh, M.W. McConley, B.D. Appleby. Accepted for publication at the 61st American Helicopter Systems Forum, 2005.

BIOGRAPHIES

Felsa B. Satlow

Senior Program Manager, Tactical Systems

Ms. Satlow has been working at Draper for over 30 years, beginning as a Software Engineer, working at the Help Desk, and developing early hypermedia applications for the military. She has been a Program Manager since 1992, and has been group leader for a group of program managers from 1998-2004. She has been managing a variety of large and small projects in diversified areas. Many of the projects have been GPS-related, in both the control or user segment, and many have been software-intensive. Recent projects in addition to the Aggressive Maneuvering program for DARPA/ITO, have been the development and maintenance of a GPS satellite testing station, a Milstar testing station upgrade, and an Automated Weaponeering research project for the Naval Air Warfare Center. Satlow has also been involved in software process improvement and assessment, including CMM and CMMI processes. She is currently working part-time on the Draper CMMI effort.

Dr. Leena Singh

Senior Member of the Technical Staff, Autonomous Control Systems Group

Dr. Singh has been at Draper in Cambridge, MA since 2001. She was previously at the United Technologies Research Center in E. Hartford, CT for 4 years. Dr. Singh was Draper Laboratory's Principal Investigator on the DARPA Software Enabled Control Program since 2002. Dr. Singh has led and supported many guidance, navigation, and control design programs for a wide variety of applications including autonomous helicopters, autonomous parafoils, threat-aware flight control of highly capable aircraft, coordinated attitude guidance for satellite constellations. She has led programs to develop, validate, and present navigation algorithms for accurate fire control systems for flexible platforms. She is presently the Principal Investigator on a program to develop accurate distributed, coordinated tracking systems of ballistic targets from a satellite constellation. Dr. Singh has supervised 3 MIT graduate students over the past 3 years and collaborated with MIT faculty members on developing advanced guidance and control methods for autonomous, threat-aware systems. She has published several papers on synthesizing computationally efficient guidance and control laws for of nonlinear and non-convex systems using convex optimization methods with hybrid, nonlinear, optimal, and model predictive control. Dr. Singh is a member of the AIAA Guidance Navigation and Control Technical Committee.

Dr. Brent D. Appleby

Principal Member of the Technical Staff, Autonomous Control Systems Group

Dr. Appleby has been at Draper for over 20 years, first as a Draper Fellow as an MIT graduate student and then becoming a full time staff member in 1990. He has been the Autonomous Control Systems group leader since 1998. Dr. Appleby was recently the technical director at Draper for the Lockheed Martin UCAR project leading the Autonomous Terrain Flight, Air Vehicle Management, and collaborating on the Autonomous Mission Planning subsystems. Dr. Appleby has led and supported many guidance, navigation, and control design tasks for a wide variety of applications including autonomous helicopters, autonomous parafoils, a gun-launched airplane, a tilt-rotor vehicle, guided projectiles, flexible space structures, satellites, the Space Shuttle autopilot, autonomous undersea vehicles, and adaptive optics. He has also led and worked on a variety of guidance, navigation, and control research projects including the development of new robust, nonlinear,

adaptive, constrained optimization, hybrid system, fuzzy, and learning control methods as well as developing robust estimation and failure detection algorithms, investigated active control techniques for high-power laser systems, and the use of active control for biomedical applications. Dr. Appleby has supervised or been a thesis committee member for over 15 MIT graduate students, has been technical monitor for several Draper-sponsored university research projects including eight years as the technical coordinator for the MIT/Draper Technology Development Partnership program. Dr. Appleby is a Lecturer in the Aeronautics and Astronautics Engineering Department at MIT. He has authored/co-authored over 20 published papers.

Dr. Marc McConley

Principal Member of the Technical Staff, Autonomous Control Group

Dr. McConley has been at Draper since 1992, first as a Draper Laboratory Fellow (1992-1996) and more recently as a full-time staff member (1996-present). Dr. McConley is presently principal investigator for a Draper Internal Navigation and Mapping research program, which is developing novel distributed sensor fusion techniques to enable rapid, precise, semi-autonomous blue-force tracking and mapping of targets, threats, and signatures in GPS-denied complex environments. In addition, Dr. McConley has technical leadership responsibility for Draper Deep Integration GPS/INS navigation algorithms at Draper. He has been the Task Leader for guidance, navigation, and control algorithm and software development for the Best Buy ATD, Ballistic Trajectory Extended Range Munition (BTERM), and Low Cost Guidance Electronics Unit (LCGEU) guided munitions programs sponsored by the Navy. In BTERM and LCGEU, Draper GN&C algorithms and electronics were flown in flight tests with two separate projectiles and successfully hit their intended targets. Dr. McConley received the annual Draper Distinguished Performance Award in 2000, 2002, and 2004.

Dr. McConley has published several papers in conferences and refereed journals on computationally efficient approaches to nonlinear control and estimation, computational complexity of nonlinear system stability analysis, and convex optimization techniques for control allocation for distributed control systems. He has also supervised MIT graduate students and collaborated with MIT faculty members on the development of advanced guidance and control approaches based on hybrid control for maneuver planning, convex constrained optimization, nonlinear dynamic inversion, neuro-dynamic programming and model-predictive control. Dr. McConley is a member of the Institute of Electrical and Electronics Engineers and the Control Systems Society.

DEPARTMENT OF THE AIR FORCE
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE OHIO 45433

19 June 2006

MEMORANDUM FOR: Defense Technical Information Center/OCA
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1. Reference: (U) Aggressive Maneuvers, ADB309356.
   - Change distribution statement from C to A
   - Replace report with the enclosed attachment.

2. Please call me at DSN 785-5766, if more information is needed.

3. Thank you for the attention given this matter.

Sharon L. Serzan

SHARON L. SERZAN, STINFO Officer
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